GROSS STRUCTURE OF THE NEUTRON ENERGY SPECTRUM AND POLARIZATION IN (d, n) REACTIONS ON INTERMEDIATE MASS NUCLEI

I. I. LEVINTOV, V. V. OKOROKOV, V. A. SMOTRYAEV, D. L. TOLCHENKOV, and I. S. TROSTIN

Institute of Theoretical and Experimental Physics

Submitted to JETP editor November 12, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **44**, 1437-1441 (May, 1963)

The spectra of neutrons produced in (d, n) reactions on neutral Co, Fe, Ni, and Cu nuclei were investigated for deuteron energies of 12.1 ± 0.4 MeV and a neutron l.s. emission angle of 10°. The measurements were performed with a multichannel time analyzer in the nanosecond range. The polarization and angular distribution of neutrons of the main gross peaks for the Co(d, n)Ni and Fe(d, n)Co reactions were also investigated. In the first case, the polarization was (−11 ± 13)% for a neutron l.s. emission angle $\theta_n = 40°$, and in the second case, it was (+7.1 ± 1.9)% for an emission angle $\theta_n = 30°$. The orbital angular momentum of the captured proton was $l_p \geq 3$.

1. INTRODUCTION

In the light of current views on the intermediate coupling, developed in particular by Lane, Thomas, and Wigner,[1] it can be assumed that the single-particle state arising from the capture of a nucleon by nuclei of intermediate mass in (d, p) or (d, n) reactions should occur in the form of groups produced by many narrow levels. The position of the "centers of gravity" of these groups and also their widths should approximately correspond to the position and reduced widths of "ideal" single-particle levels, i.e., such levels which would occur during the motion of the nucleon in the shell potential of the corresponding nucleus. The narrow levels forming the single-particle group should have the quantum numbers of the corresponding "ideal" level. Hence, in the case of medium nuclei of intermediate mass, for which the spin-orbit splitting of the "ideal" levels is 2—3 MeV and their reduced widths are $\gamma \approx \hbar^2/MR^2 \approx 1$—1.5 MeV, it can be expected that the groups of single-particle levels characterized by a definite spin and parity should have a resolvable energy. The broad ($\Delta E = 1$—2 MeV) maxima in the proton spectra from stripping reactions on nuclei with $A \sim 60$ observed by several authors[2-4] correspond to this character of the single-particle excitation. Magnetic spectrometer measurements show that these maxima split into several narrow lines (about eight in the case of ${}_{27}Co^{60}$).

As far as we know, up to the present time similar gross structures in stripping reactions have been observed only in the proton spectra. It is of interest to obtain similar data for neutrons. Proof that the narrow levels forming a group with a gross peak actually have the same spin and parity would be of particular importance for the verification of the applicability of the foregoing views to nuclei formed in some specific stripping reaction. To shed light on this question it is desirable to measure the nucleon polarization.

There is, at present, a rather large amount of experimental material on the polarization of nucleons associated with definite levels of the residual nuclei in stripping reactions. With few exceptions, the experiments showed that the polarization of the emitted nucleons in the region of the Butler peak is positive or negative, depending on whether the second nucleon is captured in a state with $j = l + 1/2$ or $j = l - 1/2$. Hence the observation of a nonvanishing polarization, upon averaging over several narrow levels of the gross peak, would be a definite argument in favor of the same quantum numbers.

We present below the results of a study of the gross structures of the neutron spectra in the (d, n) reaction on nuclei with $A \sim 60$ and the measurements of the polarization and angular distributions of neutrons associated with the gross peaks in the Co(d, n)Ni and Fe(d, n)Co reactions.

2. MEASUREMENT OF THE NEUTRON SPECTRA

The neutron spectra in the (d, n) reactions on targets of natural Co, Fe, Ni, and Cu were measured by the time-of-flight technique with a multichannel time analyzer of nanosecond range oper-

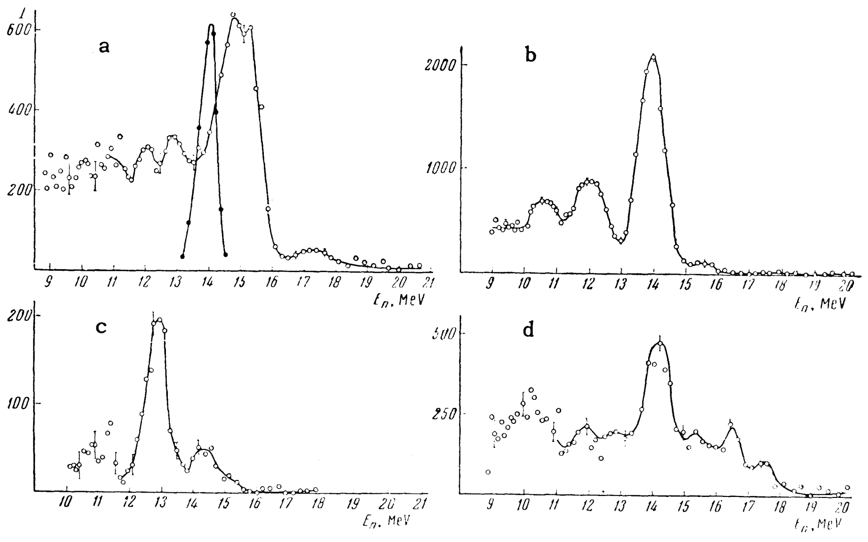

FIG. 1. Neutron spectra in the reactions: a – Co(d, n)Ni, b – Fe(d, n)Co, c – Ni(d, n)Cu, and d – Cu(d, n)Zn (I is the relative intensity normalized to a fixed counting rate of the monitor). The black circles represent the calibrated peak for checking the resolution [monoenergetic neutrons from the D(d, n)He^3 reaction].

ating on a vernier-scale principle.[1] The measurements were made with the extracted deuteron beam from the cyclotron of the Institute of Theoretical and Experimental Physics (E_d = 12.3 MeV) focused by a system of quadrupole lenses on a target situated behind a shield at a distance of ~ 11 m from the accelerator. The beam cross section at the target was ~ 5 × 3 mm with an intensity of 1 μA. Foils of the investigated elements of thickness equivalent to the range of deuterons of energy ~ 0.3 MeV were mounted on tungsten bases. The spectrometer energy scale was calibrated with monoenergetic neutrons from the D(d, n)He^3 reaction (the deuteron target thickness corresponded to the range of deuterons of energy ~ 0.6 MeV). The neutrons were recorded by a scintillation counter (FÉU-36 phototube with a stilbene crystal with a diameter of 30 mm and height of 20 mm) located 8 m from the target. All these measurements were made at a neutron emission angle of ~ 10°.

The spectra of neutrons produced in the interaction of Co, Fe, Ni, and Cu with deuterons are shown in Fig. 1. The energy resolution with which the curves were measured varied from 6% at E_n ≈ 20 MeV to 4% at E_n ≈ 8 MeV. The width of some peaks [especially the Co peak ($\bar{E}_n$ = 15 MeV) and the Fe peak ($\bar{E}_n$ = 14 MeV)] considerably exceeds the instrumental width of the peak from monoenergetic neutrons from the (d, n) reaction.

From the data it can be concluded that a distinct gross structure is present in the neutron spectra. We would like to mention two characteristics, which, if confirmed for other nuclei, should find explanation within the framework of the shell theory and the intermediate coupling model.

1. While the gross structure of the proton spectra obtained by Schiffer et al.[2] contains several peaks of approximately the same height, the neutron spectra obtained by us contain, along with peaks of comparatively small height, one peak whose height is several times that of the others.

2. There appears to be a relation between the extent to which the proton shells are populated and the intensity of the proton spectra; the $_{28}$Ni nucleus, which has a filled proton shell, captures a proton less efficiently than $_{27}$Co and $_{26}$Fe, which have unfilled shells, or $_{26}$Cu with one proton outside a filled shell (see Fig. 1).

3. MEASUREMENT OF THE POLARIZATION AND ANGULAR DISTRIBUTIONS

The polarization and the angular distributions were measured for neutrons from the Co^{59}(d, n)Ni^{60} and Fe(d, n)Co reactions with the same beam and targets as in the measurements described in the preceding section. The deuteron current was 5 μA and the beam cross section at the target was 3 × 5 mm.

The experimental arrangement is shown in Fig. 2. The polarimeter consisted of a group of triggered helium proportional counters.[7] In the present experiment, the polarimeter operated as

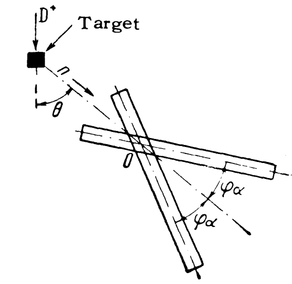

FIG. 2. Arrangement for the polarization measurements.

[1]A more detailed description of the spectrometer is given in [6].

a differential instrument which selected only one definite group of neutrons from the energy spectrum. The adjustment for the investigated neutron spectrum interval was effected through the choice of the helium pressure in the counters. The pressure was set so that the range of the He^4 recoil nuclei emitted at $\varphi_\alpha = 20°$ (l.s.)[2)] from collisions with neutrons of analyzed energy (E_0) was $\sim 2/3$ of the effective length of the counter. It turned out that the contribution from neutrons of energy $E > E_0$ in the investigated energy interval was no greater than 10—20%. Neutrons of energy $E < E_0$ were not recorded. The counter pressure was varied from 3 to 14 atm, which corresponded to neutron energies between 5.9 and 18.8 MeV.

The polarimeter was calibrated with α particles from Pu^{239}. The calibration source was placed at the midpoint of the effective length of the counter. Hence, the energy lost in the counters by the α particles from Pu^{239} was less than the energy of the He^4 recoil nuclei for all the investigated intervals of the neutron spectrum. The amplitude resolution of the counters was $\sim$ 8%. The width of the energy intervals for which the polarization was measured was between 1 and 2 MeV.

The value of the neutron polarization in the $Co^{59}(d, n)Ni^{60}$ reaction is shown in Fig. 3 as a function of the energy interval (E_n). The neutron l.s. emission angle was $\theta_n = 40°$. The neutron polarization in the Fe(d, n)Co reaction, measured only at an energy corresponding to the main gross peak ($\bar{E}_n$ = 14 MeV), proved to be $P_n = +(7.1 \pm 1.9)\%$ at $\theta_n = 30°$ and $P_n = +(4.7 \pm 3.3)$ at $\theta_n = 50°$. The $n\alpha$ scattering phase shifts were taken from Seagrave.[8] The mean deuteron energy was 12.1 ± 0.4 MeV. The positive direction of the normal was defined as $\mathbf{n} = \mathbf{k}_d \times \mathbf{k}_n$. Since the measurement was made under conditions of good geometry,[9] the corrections for the anisotropy of the neutron angular distribution were not taken into account. The maximum of the polarization in the Co(d, n)Ni reaction corresponds to the position of the main gross peak in the neutron spectrum. The sign of the polarization corresponds to the capture of a proton by $_{27}$Co and $_{26}$Fe in the $j = l - 1/2$ and $l + 1/2$ states, respectively.

For the neutron angular-distribution measurements, the counters were set at an angle $\varphi_\alpha = 0$. The pressure was chosen in the same way as in the polarization measurements. The neutron angular distributions of the main gross peaks of the Co(d, n)Ni ($\bar{E}_n$ = 15 MeV) and Fe(d, n)Co ($\bar{E}_n$ = 14 MeV) reactions, together with the theoretical curves, are shown in Figs. 4a and 4b. The angular distributions were calculated according to Lubitz.[10]

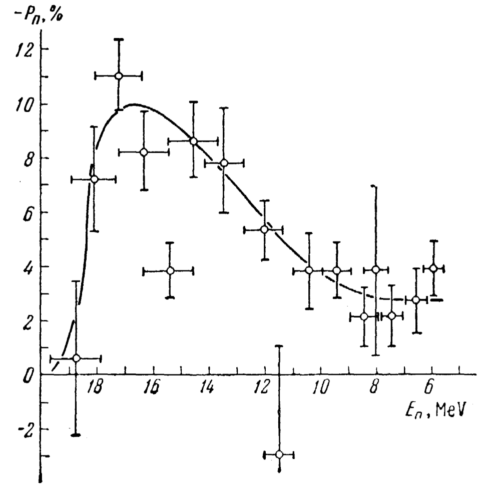

FIG. 3. Neutron polarization in the $Co^{59}(d, n)Ni^{60}$ reaction (E_d = 12.1 ± 0.4 MeV).

The obtained values $l_p = 3$ agree well with the shell model in both cases, since the filling of the 1f shell for protons ends with the $_{28}$Ni nucleus. On the other hand, the large values of l_p lead to a comparatively small polarization effect, in view of the possible smallness of the quantity $\langle m \rangle$, i.e., the mean value of the projection of the orbital angular momentum on the direction of the normal to the reaction plane [see formulas (3) and (4) of [11]]. The fact that the ratio of the positive value of the neutron polarization in the Fe(d, n)Co re-

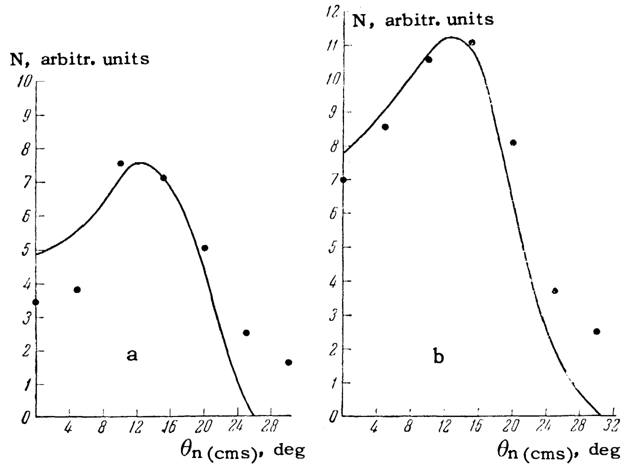

FIG. 4. Angular distributions of neutrons from the main gross peaks: a – Co(d, n)Ni, the curve was calculated for $l_p = 3$ and r_0 = 12.2 F; b – Fe(d, n)Co, the curve was calculated for $l_p = 3$ and r_0 = 11.4 F.

[2)]The angle $\varphi_\alpha = 20°$ is the angle of rotation of the analyzer counters approximately corresponding to the maximum asymmetry of the scattering on He^4 (see [7]).

action to the negative value of the polarization in the Co(d, n)Ni reaction is smaller than unity (~ 0.7) also agrees with the distorted-wave theory and the value of l_p. According to the results of Huby et al.,[11] we have $P_+/P_- = l_p/(l_p + 1) = 3/4$.

Hence, on the whole, the obtained experimental data are in agreement with the views on the existence of gross peaks in the neutron spectra from the (d, n) reactions to which definite quantum numbers can be assigned.

The authors express their deep gratitude to the cyclotron crew of the Institute of Theoretical and Experimental Physics for the faultless operation of the accelerator and to V. S. Repin, I. V. Malyutin, and I. I. Mitrofanov for aid in the measurements.

[1] Lane, Thomas, and Wigner, Phys. Rev. **98**, 693 (1955).

[2] Schiffer, Lee, and Leidman, Phys. Rev. **115**, 427 (1959).

[3] R. A. Peck and J. Lowe, Phys. Rev. **114**, 847 (1959).

[4] J. P. Schiffer and L. L. Lee, Jr., Phys. Rev. **115**, 1705 (1959).

[5] Enge, Jarrell, and Angleman, Phys. Rev. **119**, 735 (1960).

[6] V. V. Okorokov and D. L. Tolchenkov, PTÉ, in press.

[7] Levintov, Miller, and Shamshev, JETP **32**, 274 (1957), Soviet Phys. JETP **5**, 258 (1957); Trostin, Smotryaev, and Levintov, JETP **41**, 725 (1961), Soviet Phys. JETP **14**, 524 (1961).

[8] J. D. Seagrave, Phys. Rev. **92**, 1222 (1953).

[9] I. I. Levintov and I. S. Trostin, JETP **40**, 1570 (1961), Soviet Phys. JETP **13**, 1102 (1961).

[10] C. R. Lubitz, Numerical Table of Butler-Born Approximation Stripping Cross-Section, Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan, 1957.

[11] Huby, Refai, and Satchler, Nuclear Phys. **9**, 94 (1958/1959).

Translated by E. Marquit
230